09/889229 PCT/SE 00/00047

REC'D 23 FEB 2000

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(21) *Patentansökningsnummer* *9900121-6*
Patent application number

(86) *Ingivningsdatum* *1999-01-14*
Date of filing

Stockholm, 2000-02-11

För Patent- och registreringsverket
For the Patent- and Registration Office

Emma Johnsson

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Description

Molecular imprinting is an established technique for the preparation of synthetic receptors with high affinities and specificities for various analytes of interest. During the free radical polymerization commonly used in the imprinting process, the incorporation of template-complementary functionality into the polymer matrix, which is the key to ligand re-binding, is guided by the template molecules themselves, since they form complementary guest-host complexes with the functional monomers. Following removal of the template from the polymer matrix, the crosslinked polymeric host can rebind the original template very specifically (Figure 1) [1-3]. Depending on the nature of the interactions guiding the assembly of the guest-host complex and the subsequent recognition of the target ligand, molecular imprinting strategies can be divided into two major categories: covalent and non-covalent imprinting approaches. A semi-covalent imprinting method is also possible, where one can use covalent interactions for the preparation of the imprinted polymer and non-covalent interactions for the subsequent re-binding of ligands of interest [4]. These molecularly imprinted receptor analogs are easy to produce and very stable, and are therefore superior to natural receptors in many respects. Molecularly imprinted polymers have been used for chromatographic separation [5], in biomimetic sensors [6], in catalyzing chemical reactions [7], in solid phase extraction for sample enrichment/clean-up [8], in the screening of combinatorial chemical libraries [9], for *in situ* product removal during biotransformation processes [10], and down-stream product purification [11]. They also have great potential for drug determination using for instance ligand competition assays [12].

Imprinted polymers are usually prepared in the form of a monolith which is then ground and sieved to the desired particle size. The grinding and sieving process is time-consuming and yields only moderate amounts of useful imprinted polymer. The polymer particles obtained are also irregularly-shaped, which is not ideal for chromatographic purposes. Furthermore, the grinding process may

also be detrimental to some of the binding sites. Suspension polymerization in perfluorocarbon liquid continuous phases has been introduced to address some of these issues [13]. Although this method delivers good yields of spherical particles with controlled particle sizes, it is not a straightforward method in that it requires considerable optimisation. The perfluorocarbon dispersing phase is also somewhat expensive. Other imprinting methods leading to spherical particles with controlled sizes include emulsion polymerization in aqueous media, and seeded emulsion polymerization. However, they involve either the use of stabilizers or multi-step operations, which are neither straightforward nor broadly applicable for imprinting.

This patent application describes a novel method for preparing molecularly imprinted microspheres using surfactant-free precipitation polymerization and the applications of these imprinted microspheres. Precipitation polymerization, sometimes being called surfactant-free polymerization, can be used to prepare monodisperse microspheres with controlled particle diameters, typically within the 0.1-10 μm range [14-17]. The mechanism for particle formation and growth resembles that of dispersion polymerization, except that the particles are stabilised against coagulation by their rigid, crosslinked surfaces, rather than by any added stabilizers. These microspheres are easy to prepare and are free from any adsorbed surfactants. Significantly, neither polymer grinding nor sieving steps are necessary following polymerisation, therefore the preparation of molecularly imprinted microspheres by this method is much more efficient in terms of yield and much less time-consuming to perform. In conventional molecular imprinting protocols, the yield of imprinted polymer with the desired particle size range following successive grinding and sieving operations is usually less than 50%. In contrast, the present method allows polymer yields upwards of 85% to be attained. The regular size and shape of the particles can facilitate system homogenisation and is advantageous for mass transfer in ligand rebinding processes. It also offers benefits in chromatographic applications.

Both reversible covalent and non-covalent interactions can be utilised during the imprinting process when using precipitation polymerization. The semi-covalent strategy can also be used. Functional monomers for reversible covalent interactions include boronate ester-forming monomers, Schiff base-forming monomers, and carbonate-forming monomers. For non-covalent interactions, hydrogen bond-forming monomers, ion-pair forming monomers, metal-chelating monomers, as well as hydrophobic monomers can be used (Figure 2). Various crosslinkers can be used depending on the solvent employed as a porogen. Polymerization can be initiated in a variety of ways, typically via thermal or photochemical means, and both water-soluble and organic solvent miscible initiators can be used, depending on the solvents employed. To obtain spherical microspheres with good recognition behaviour, efficient crosslinking normally has to be ensured. Typically this is achieved by using a high degree of crosslinking. For some purposes, however, a much lower crosslinking density can still yield microspheres with satisfactory molecular recognition capabilities.

Compared to conventional imprinting methods, far greater amounts of solvent are used in precipitation polymerisation protocals to prepare the imprinted microspheres. Both aqueous and non-aqueous solvents can be used for different target print molecules. When the non-covalent strategy is used, except where the hydrophobic effect is of interest, less-polar organic solvents, for example dichloromethane and acetonitrile are generally most satisfactory. Imprinting via other strategies can readily use aqueous and polar non-aqueous solvents. The total monomer volume in the polymerization solution is generally within the range 1 - 10% v/v with respect to the polymerization solvent, to prevent aggregation of the microspheres. The amount of print molecule can be, though not necessarily, so high as to saturate the solvent containing the functional monomer and the crosslinker at the polymerization temperature in order to provide a high load capacity for the resulting imprinted microspheres. On the other hand, a poor solvent for the print molecule can be introduced as a co-solvent if required, to reduce the solubility of the print molecule and therefore to reduce the amount of print molecule required. This may be an attractive approach when one is using an expensive print molecule, for example, hexane can be added to acetonitrile to make the print

molecule much less soluble while the complex formation between the functional monomer and the print molecule in the non-covalent approach is not sacrificed. By controlling various reaction conditions, such as the solubility parameters of the resulting polymer and that of the solvent, the nucleation and growth behaviour of the polymer particles can be tailored to deliver monodisperse microspheres of controlled particle diameter and porosity that retain high affinity and specificity for the print molecules.

The molecularly imprinted microspheres can be used in various applications. These artificial receptors can readily replace their natural counterparts in many instances. Their regular size and shape allows better reproducibility in various assays. Non-limiting examples of applications of molecularly imprinted microspheres, including monodisperse microspheres, are: 1) as stationary phases or modifiers in capillary electrophoresis; 2) as recognition components in biomimetic sensors; 3) as catalysts to facilitate chemical/biochemical reactions; 4) as probes for cell targeting when they are dyed or made magnetic; 5) for drug determination using competitive ligand assay; 6) as bio-compatible carrier for controlled drug release; 7) as binding components to prepare composite materials for affinity purification/isolation of target compounds.

Example 1

Preparation of anti-theophylline microspheres

Acetonitrile (50 mL) is mixed with methacrylic acid (MAA, 372.5 mg) and trimethylolpropane trimethacrylate (TRIM, 627.5 mg) in a borosilicate glass tube. Theophylline (115 mg) is suspended in the solution and dissolved after sonication at 60°C. The initiator, azobisisobutyronitrile (AIBN, 17.5 mg) is dissolved, the solution purged with nitrogen for five minutes and the tube sealed under nitrogen. Polymerization is induced by placing the tube in a water bath preset at 60°C and continued for 24 hours. The microspheres formed are collected by centrifugation at 8000 rpm for 10 minutes

using a RC5C superspeed refrigerated centrifuge from BECKMAN (Palo Alto, CA, USA). The print molecule is thoroughly extracted by washing repeatedly with methanol containing 10% acetic acid (v/v), followed by a final wash in acetone. These successive centrifugation and decanting steps extract the print molecule from the polymer. The anti-theophylline microspheres obtained are monodisperse and have an average diameter of 0.2 μm. The microspheres are finally dried *in vacuo*. The reference (control) microspheres are prepared and treated in exactly the same way, except that no print molecule is used in the polymerization stage.

Example 2

Preparation of anti-theophylline microspheres

Acetonitrile (50 mL) is mixed with MAA (372.5 mg) and TRIM (627.5 mg) in a borosilicate glass tube. Theophylline (11.5 mg) and AIBN (17.5 mg) are dissolved in the solution. The solution is purged with nitrogen for five minutes and the tube sealed under nitrogen. Polymerization is induced by UV irradiation (350 nm) at 20°C using a RMA-400 Rayonet photochemical reactor from Southern New England Ultraviolet Co. (Bradford, CT, USA) and continued for 24 hours. The microspheres obtained are treated in the same way as per example 1 to remove the print molecule. The reference (control) microspheres are prepared and treated in exactly the same way, except that no print molecule is used in the polymerization stage.

Example 3

Preparation of anti-17β-estradiol microspheres

Acetonitrile (50 mL) is mixed with MAA (372.5 mg) and TRIM (627.5 mg) in a borosilicate glass tube. 17β-Estradiol (250 mg) and AIBN (17.5 mg) are dissolved in the above solution. The solution

is purged with nitrogen for five minutes and the tube sealed under nitrogen. Polymerization is induced by UV irradiation (350 nm) at 20°C using a RMA-400 Rayonet photochemical reactor from Southern New England Ultraviolet Co. (Bradford, CT, USA) and continued for 24 hours. The microspheres obtained are treated in the same way as per example 1 to remove the print molecule. The anti-17β-estradiol microspheres obtained are monodisperse and have an average diameter of 0.3 μm (Figure 3). The reference (control) microspheres are prepared and treated in exactly the same way, except that no print molecule is used in the polymerization stage.

Example 4

Competitive radioligand assay using anti-theophylline microspheres from example 1

The binding capacity of the anti-theophylline microspheres from example 1 is estimated from saturation studies. Varying amounts of the microspheres are incubated overnight and at room temperature with 16.2 pmol (685 Bq) [8-^{3}H]theophylline in 1 mL acetonitrile, using polypropylene microcentrifuge tubes. A rocking table ensured gentle mixing. The microspheres are then separated by centrifugation at 14,000 rpm for five minutes, 500 μL supernatant mixed with 10 mL scintillation liquid, Ecoscint O (National Diagnostics, Manville, NJ, USA), and the radioactivity then measured using a model 2119 RACKBETA β-radiation counter from LKB Wallac (Sollentuna, Sweden). The amount of anti-theophylline microspheres required to bind half of the added radioligand is estimated to be 5 mg, while an equivalent amount of the reference polymer binds less than 10% of the added radioligand.

The theophylline-imprinted microspheres are suspended in acetonitrile (25 mg/mL) and sonicated to form a polymer stock suspension, from which 200 μL was transferred into each microcentrifuge tube. Varying amounts of non-radiolabelled ligand, including theophylline, theobromine, xanthine and caffeine, and 16.2 pmol (685 Bq) [8-^{3}H]theophylline are added, and the final volume adjusted to

1 mL with acetonitrile. The competitive binding is allowed to proceed overnight by incubation at ambient temperature, using a rocking table for gentle mixing. The amount of bound radioligand is estimated by measuring the radioactivity from 500 μL supernatant following centrifugation at 14,000 rpm for five minutes. The high specificity of the anti-theophylline microspheres can be evaluated by comparing the IC_{50} value of compounds closely-related to the print molecule, with IC_{50} being the ligand concentration that can displace 50% of the bound radioligand from the imprinted microspheres. Figure 4 shows the displacement of radioligand binding to molecularly imprinted microspheres under equilibrium condition. B/B_0 is the ratio of the amount of radioligand bound in the presence of displacing ligand, B, to the amount bound in the absence of displacing ligand, B_0.

Example 5

Competitive radioligand assay using anti-theophylline microspheres from example 2

The same procedure as used in example 4 is followed, except that the microspheres are from example 2. The amount of anti-theophylline microspheres required to bind half of the added radioligand is estimated to be 10 mg, while an equivalent amount of the reference polymer binds less than 20% of the added radioligand.

The theophylline-imprinted microspheres are suspended in acetonitrile (50 mg/mL) and sonicated to form a polymer stock suspension, from which 200 μL was transferred into each microcentrifuge tube. The same competitive binding assay as in example 4, using theophylline as the cold ligand, is followed. A calibration curve for theophylline similar to the one in Figure 4 is obtained, although the non-specific binding is slightly higher (Figure 5).

Example 6

Competitive radioligand assay using anti-17β-estradiol microspheres from example 3

Varying amounts of the microspheres were incubated overnight and at room temperature with 417 fmol (1110 Bq) [2,4,6,7-^{3}H(N)]estradiol in 1 mL acetonitrile, using polypropylene microcentrifuge tubes. Other conditions are the same as used in example 4. The amount of anti-17β-estradiol microspheres required to bind half of the added radioligand is estimated to be 30 mg, while an equivalent amount of the reference polymer binds less than 12% of the added radioligand.

The 17β-estradiol-imprinted microspheres are suspended in acetonitrile (150 mg/mL) and sonicated to form a polymer stock suspension, from which 200 μL was transferred into each microcentrifuge tube. Varying amounts of non-radiolabelled ligand, including 17β-estradiol, 17α-estradiol and 17α-ethynylestradiol, and 417 fmol (1110 Bq) [2,4,6,7-^{3}H(N)]estradiol are added, and the final volume adjusted to 1 mL with acetonitrile. Other conditions are the same as used in example 4. Specificity of the anti-17β-estradiol microspheres is signified in Figure 6.

Claims

1. A method of producing molecularly imprinted microspheres with diameters typically between 0.01 - 10 μm, using surfactant-free precipitation polymerization. The specific binding sites are created using print molecules that form either non-covalent, reversible covalent or "semi-covalent" interactions with the functional monomer as templates.
2. A method of producing molecularly imprinted microspheres, where the total volume of the polymerizable monomer/crosslinker is typically kept within 0.01 - 20% v/v to that of the reaction solvent. The reaction solvent employed is either aqueous or non-aqueous, and is either single component or composed of multiple solvents.

3. A method of producing molecularly imprinted microspheres, where the interactions between print molecules and functional monomers utilised for imprinting and re-binding can be either reversible covalent, non-covalent, or both. Multiple interactions of different characters can be simultaneously utilised. Different functional monomers can be employed simultaneously, in addition to using single functional monomer.
4. A method of producing molecularly imprinted microspheres, where the solubility of print molecules in the reaction solvent is adjusted by changing the composition of the reaction solvent.
5. A method of producing molecularly imprinted microspheres, where the polymerization can be induced by heat, by UV, by γ radiation or by chemical methods. Free-radical polymerization, ionic polymerization, coordination polymerization, step growth polymerization or related method are used to prepare molecularly imprinted microspheres without using surfactant.
6. A method of producing molecularly imprinted microspheres, where monodisperse microspheres with desired particle sizes can be produced by controlling the nucleation and particle growth process of the resulting polymer. This is achieved through adjusting the composition of functional monomer/crosslinker/solvent system, as well as reaction conditions, in order to change the solubility of the growing polymer chains. The polymerization conditions are controlled in such a way as to avoid aggregation of the microspheres.
7. Use of molecularly imprinted microspheres to replace the conventional imprinted polymers in various applications.
8. Use of molecularly imprinted microspheres for the screening of chemical libraries, for catalysis, for facilitated synthesis, for analyte determination using competitive ligand binding assay and agglutination assays.
9. Use of molecularly imprinted microspheres as stationary phase or modifier in capillary electrophoresis, capillary electrochromatography and HPLC analysis, as recognition component in biomimetic sensors, as affinity-labelled probe for targeting cell or other biological interests.
10. Use of molecularly imprinted microspheres as binding entities for the preparation of composite materials.

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Abstract

This patent application describes a method for preparing molecularly imprinted microspheres via precipitation polymerization in the absence of any added surfactants. Highly specific, molecularly imprinted microspheres in the micron-scale size range can be produced quickly, cleanly and in excellent yield by this method, and the regular particle size and shape of the microspheres obtained is advantageous in several ways. These artificial receptors can readily replace biologically derived receptors in many applications and are therefore highly attractive. Several possible applications are describe herein.

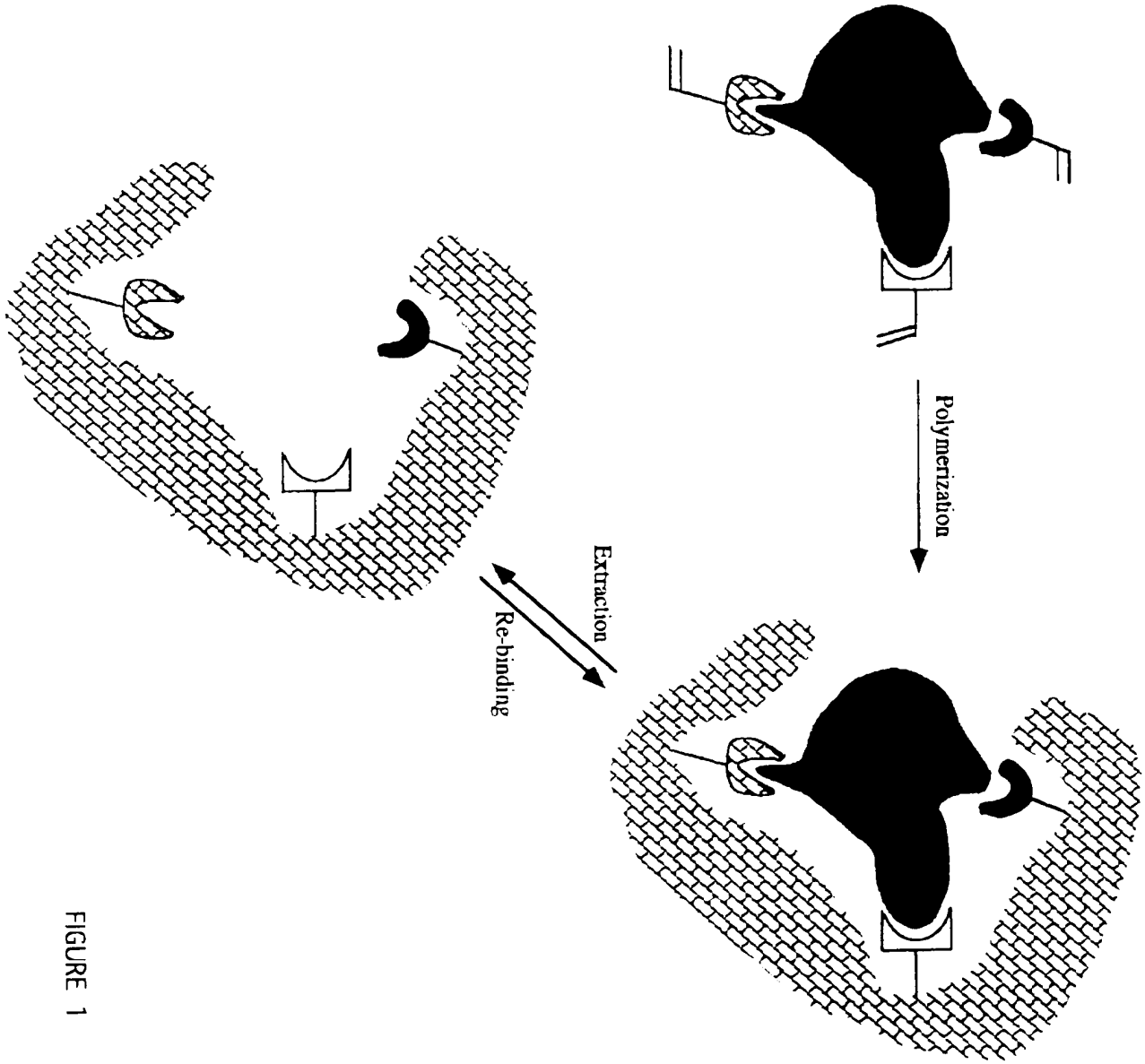
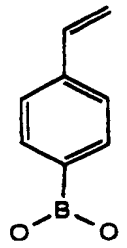


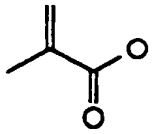
FIGURE 1

Boronate ester-forming monomer

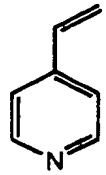


4-Vinylphenylboronic acid

Hydrogen bond-forming and ion-pair forming monomers

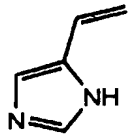


Methacrylic acid

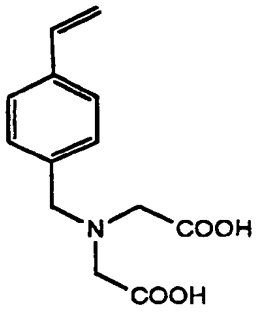


4-Vinylpyridine

Metal-chelating monomers



4-Vinyl imidazole

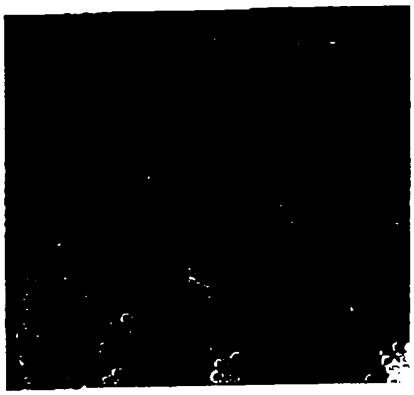


4-Vinylbenzyl-iminoacetic acid

FIGURE 2

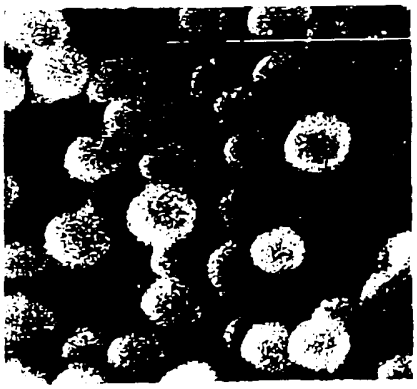
46 46 2224611

FIGURE 3



A

Magnification
7,500 x



B

Magnification
30,000 x

46 46 2224611

FIGURE 4

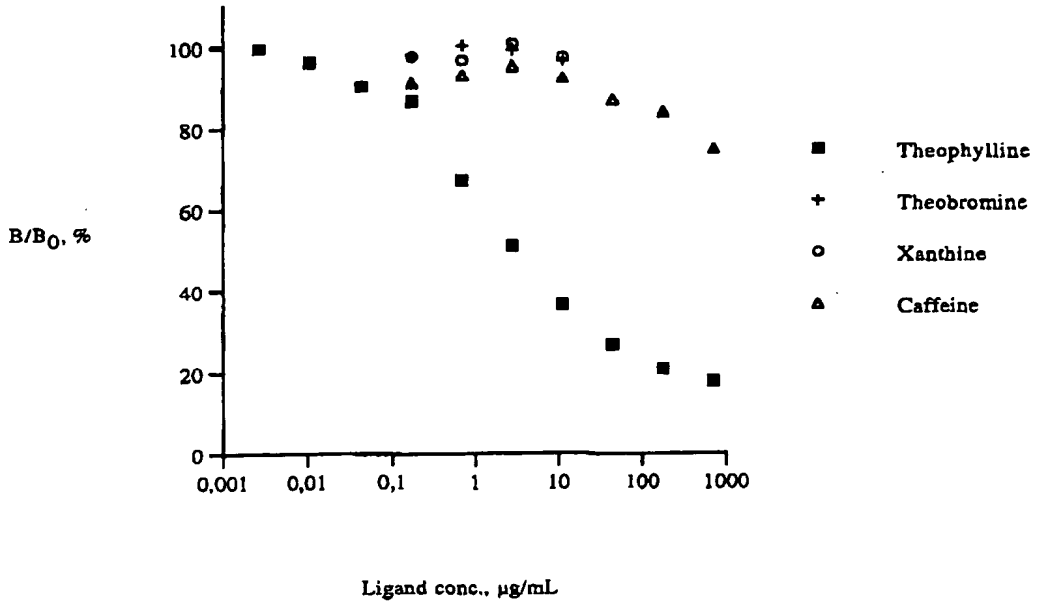


FIGURE 5

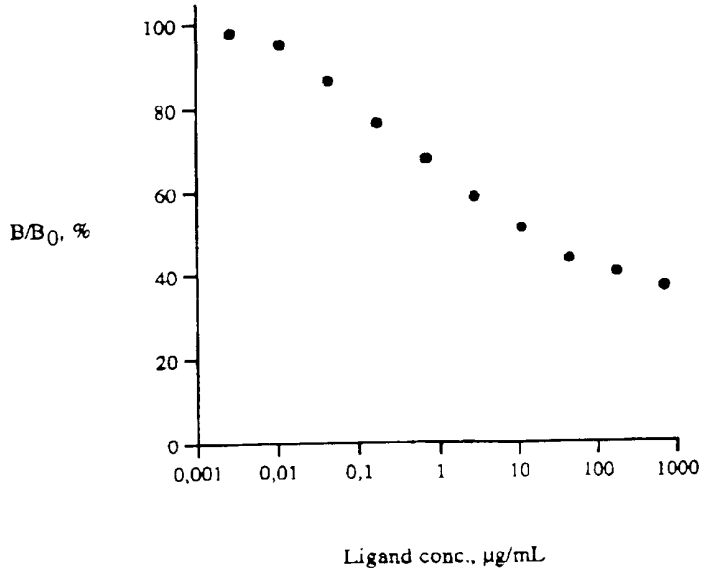


FIGURE 6